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SCIENCE & TECHNOLOGY POLICY INSTITUTE

Review of CFD Capabilities

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PREFACE

This document was prepared for the Office of Science and Technology Policy, Executive Office of the President, under a task titled "Assessment of CFD Capabilities."

CONTENTS

Review of CFD Capabilities

OSTP

19 May 2005

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Outline

- **Study Overview**
- Executive Summary and Review of Overall Findings
- Impact and History of CFD
- Metrics for Evaluating CFD Development
- Conclusions

Tasking

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- STPI is a federally funded research and development center, operated by the Institute for Defense Analyses
- This work was commissioned by OSTP on 5 November 2004 and is intended to:
  - Evaluate the state of the art of computational fluid dynamics (CFD) to understand the role it currently plays in the aircraft design process and identify specific areas of development that would improve its contribution during the next 20 years. Develop an understanding of:
    - The limitations and opportunities with CFD
    - Appropriate metrics for evaluating the capabilities of both CFD and physical testing
    - Investments required to develop CFD capabilities to better support aerospace R&D

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The study evaluated the current state of computational fluid dynamics (CFD) and the likely opportunities to further improve CFD over the next 20 years. This briefing summarizes those findings and includes:

- Overall findings

- Description of approaches to CFD, including historic development of CFD capabilities and likely future development paths

- Discussion of metrics for characterizing CFD, including impact on the design process, the state of maturity of CFD, and the cost of CFD relative to physical test infrastructure

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Approved for public release; distribution unlimited. (14 November 2005)

Task Participants

- Science and Technology Policy Institute
  - Dan Garretson (Task Leader)
  - Kay Sullivan

- Operational Evaluation Division
  - Hans Mair

- Science and Technology Division
  - Christopher Martin
  - Jeremy Teichman

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The analysis that follows was conducted by a cross-divisional team from the Institute for Defense Analyses.

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Task Approach

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- Review existing studies and analyses
- Supplement with a number of expert interviews
  - Government (primarily NASA) labs
  - Academic experts
  - Industry practitioners
- Characterize the state of the art for CFD
  - Use Technology Readiness Level (TRL) approach as familiar framework for assessment. Analysis structure:
    - Identify the types of data required for aircraft design
    - Characterize the usefulness (in terms of TRL) of CFD for gathering/generating the required data
    - Identify the shortcomings/opportunities for CFD
  - Evaluate trends in computing capability relative to CFD requirements
  - Evaluate cost of CFD vs. cost of physical test infrastructure for generating design data

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As part of the approach shown on this slide, the team spoke with a number of CFD experts throughout industry, government, and academia:

- Northrop Grumman—Dave Solomon, Dale Lorincz
- Lockheed Martin—Pradeep Raj
- Boeing—Ray Cosner, Steve Barson, Mori Mani
- NASA Langley—Rich Wahls, Dave Schuster, Mujeeb Malik, Jim Thomas, Jim Pittman, Peter Gnoffo
- U.S. Air Force Arnold Engineering Development Center—Ed Kraft, Tracy Donegan, Jere Matty
- U.S. Air Force Research Laboratory—Jack Benek
- U.S. Army AFFD—Bob Ormiston, Wayne Mantay (NASA Langley)
- Sandia National Laboratories—Bill Oberkampf
- NASA Ames—Unmeel Mehta, Guru Guruswamy
- American Helicopter Society—Rhett Flater

- Auburn University—Chris Roy
- MIT—Jaime Peraire
- Caltech—Paul Dimotakis
- University of Michigan—Carlos Cesnick
- University of Maryland—Indirjit Chopra
- George Mason University—Rainald Löhner
- Stanford University—Antony Jameson
- University of Minnesota—Graham Candler
- Fluent—Gregory Stuckert
- National Defense University—Don Daniel
- National Institute for Aerospace—David Peake
- Independent Consultant, Retired Northrop Grumman V. P.—Brian Hunt

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Caveats

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- This study focused on external aircraft flows
  - Fixed-wing, rotary-wing, and hypersonic aircraft were considered
  - Combustion and other issues of internal (engine) flow were not addressed directly

- This study did not evaluate wind tunnel facilities or their capabilities
  - Comparisons between CFD and wind tunnel testing were only made to investigate how each relates to the overall aircraft design process

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Although combustion and internal (engine) flow are critical to aircraft design and highly reliant on CFD and wind tunnel testing, these flows were not addressed directly by this study. We did receive some peripheral input on the topic and, where relevant, have incorporated it.

In addition, this study did not evaluate wind tunnel facilities or their capabilities directly. For more information on the current U.S. wind tunnel capability, see "Wind Tunnel and Propulsion Test Facilities," by Philip Anton, RAND (MG-178).

Outline

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Executive Summary

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- State-of-the-art CFD *can*
  - Predict aircraft performance at cruise conditions
  - Narrow design space for preliminary airframe design
  - Validate incremental changes to existing designs
- For full aircraft design, CFD falls short
  - Reynolds-averaged Navier Stokes (RANS) methods cannot accurately simulate all flight conditions
  - Wind tunnels often provide data more rapidly/promptly and cost effectively (even where CFD provides accurate data)
- CFD simulations require physical validation
  - Calibration of RANS approximations
  - Development of new simulation methods
- Directions for CFD
  - RANS approaches (currently dominant) are algorithmically mature
  - Large eddy simulation (LES) approaches are expected to dominate high-end simulation in 10 to 15 years
  - Model-independent improvements hold the promise of payoffs independent of simulation approach
    - Grid generation and dynamic grid adaptation
    - Improved understanding of laminar to turbulent flow transition

The points in thise chart will be covered in more detail throughout the presentation.

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Overall Findings

- Current CFD methods have improved aircraft designs and the design process
  - CFD is widely used for modeling situations where flow is steady and attached (aircraft cruise conditions, propulsion integration, and environmental control systems)
- CFD methods are widely expected to shift from RANS to LES simulations over the next 10+ years
- Improvements in CFD methods require ground or flight tests for validation

Widespread Current CFD Use

CFD is already an integral part of the airframe design process, not an auxiliary capability. CFD is used to get preliminary data in the initial phase of design and to winnow the field of proposed configurations. Depending on which perspective the process is viewed from, this either saves a great deal of time and money that would otherwise go toward physical testing, or it enables higher performance, more challenging designs for a fixed physical-test time and money budget.

Validation

Each new CFD method will need to be validated by demonstrating its ability to accurately model relevant physical flows. This requires physical test infrastructure capable of delivering test data of the precision and quality necessary to confirm the claimed capabilities of the CFD code. As improvements in CFD begin to enable simulations of greater fidelity than the measurement fidelity of current physical test infrastructure, concurrent improvements in physical test infrastructure will be required to keep pace with the validation of new methods. In particular, CFD codes for solving unsteady flow problems, such as modeling of maneuvering aircraft, will require validation methods beyond the reach of current ground test infrastructure, which is limited in the types of maneuvers it can replicate. CFD codes for hypersonic flight will require validation methods, even for steady flow, in regimes that current and planned wind tunnels cannot reproduce.

Overall Findings (continued)

- Assuming computing power follows historical trend lines, complete aircraft design database generation using CFD is still 40+ years off

- Direct numerical simulation (DNS) is not likely to be achievable in aircraft applications for 20+ years and is not likely to have significant operational impact for 30–40 years

The projected advances in computer speed and CFD computational requirements are described in more detail later in the presentation. LES of full aircraft are theoretically possible today, based on computer speed and projected grid size, and codes for that purpose are in the early stages of development. Direct numerical simulation (DNS) is currently only possible on very simple problems. Assuming computing power follows historical tends, it will be another 15 to 20 years before the computational resources are available to even begin developing DNS codes for flows around an aircraft. Once LES or DNS are demonstrated to be feasible on aircraft geometries, there will be further lag time as the new techniques replace older design tools in industry practice and begin to have a significant operational impact on the design of new aircraft.

Overall Findings (continued)

- A priori predictions with CFD currently struggle with:
  - Separated flows
  - Turbulence
  - Boundary-layer transition and heat transfer
  - Aeroelastic phenomena
  - Icing
  - Reacting flows
  - Acoustics and vibration

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Separated Flows

Regions of separated flow dominate current computational drag prediction uncertainties. During noncruise conditions, such as takeoff, landing, and maneuver, separated flows abound, contributing to the difficulty of faithfully simulating such flight conditions. RANS calculations have inherent assumptions about boundary layers, which are violated in separated flow. RANS use requires tuning of parameters for each flow environment to yield usable predictions. General calculation of separated flow will require use of higher fidelity models such as LES or DNS.

Turbulence Model

Most computationalists desire a better, more general turbulence model for use with RANS (currently, many turbulence models exist, and the selection of the most appropriate model for the flight condition of interest requires an expert). Also, there is debate about whether significant improvement in the overall solution accuracy is achievable, given the inherent simplifications made by RANS computations. Hybrid RANS–LES methods are under development to exploit the greater capabilities of LES in regions poorly served by RANS.

Boundary-Layer Transition

Integral methods do exist for prediction of boundary-layer transition from laminar to turbulent flow. Reduced-order models currently used in practice provide insufficient reliability in many cases. More complicated methods based upon stability analysis have demonstrated much greater reliability; however, they require far more intricate calculations consuming commensurately more computational effort (one expert estimated that a three-dimensional stability calculation for a single boundary layer could require as much computational effort as a full aircraft, three-dimensional RANS solution).

Aeroelastic Phenomena

Growing use of more flexible composite structures in airframe design increases the importance of accurate calculation of dynamic airframe deformation in prediction of flight-performance characteristics. UAVs in particular utilize these lightweight, flexible airframe constructions. To successfully complete flow calculations for deforming airframes, the computational grid must be able to

dynamically deform nonlinearly to accommodate the evolving solid geometry. Current CFD methods are unable to accommodate such deformation, and calculations typically crash when such deformations are encountered.

Icing

Computational models for ice formation on the wings of aircraft are not well developed. Modeling ice accretion is especially difficult because of the wide range of atmospheric conditions that have to be incorporated into the analytical model to accurately predict the ice buildup. Furthermore, the boundary-layer transition point will move in response to the presence of ice in ways that are not well understood. Advances in laminar-to-turbulent modeling will help, but work still needs to be done to improve the prediction of ice buildup on the leading edge. Simulating ice formation also presents grid generation difficulties. The grid must be moved to account for the growing ice level, which requires adaptive grid generation. In addition, the ice does not necessarily end with a smooth transition to the physical wing, which results in a possible discontinuity in the surface model.

Reacting Flows

Chemical reaction rates are dramatically influenced by the effectiveness of mixing of the chemical reactants. To successfully predict chemical compositions and energy released by reactions, CFD methods will need to accurately model and track the mixing of multicomponent flows at scales below the resolution of the overall flow calculation in ways that current methods entirely eschew. Accurate prediction of chemical composition is clearly important in internal engine flow, where combustion plays a central role in the flow's purpose. Accurate prediction is particularly important in scramjets, where the window of effective engine operation is extremely narrow. Chemical composition plays a less obvious but equally critical role in high-speed external flows because shock-wave structure and behavior are determined by chemical composition. Prediction of shock-wave position and evolution is essential to aircraft performance modeling. In hypersonic flight, high temperatures lead to flow-field chemistry, which must be accurately modeled to understand flight dynamics.

Acoustics

Calculation of the acoustic emissions of an aircraft can be extremely challenging because the acoustic energy represents a minuscule fraction of the total energy in the flow—less than 1 part in 1,000. In military rotorcraft, where the level of acoustic

signature can be the determining factor in the tactical utility of the helicopter, noise prediction hinges upon the ability to track vortices shed from one rotor-blade through their impingement on successive rotor blades. Current methods fail to track vortices for a sufficiently long time to model this phenomenon, in part because of the artificial viscosity added to the models to prevent unstable simulations. It is readily apparent that addition of extra, nonphysical dissipation might well disrupt efforts to track energy constituting less than 1 part in 1,000 of the total flow energy. Use of LES rather than RANS may be required to effectively capture this effect.

Vibration

This is a focal issue for rotorcraft, which currently carry significant ballast for passive damping. The elimination of passive damping mass through better a priori prediction and mitigation of vibrational effects would increase payload and reduce life-cycle costs. Vibration is also a major issue in stores release.

Overall Findings (continued)

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- CFD costs are driven by high marginal costs per data point
  - Automation technologies (e.g., gridding, run monitoring, post-processing) should improve CFD usefulness by reducing the time required to generate a solution or sets of solutions
  - Many automation technologies are applicable to any CFD algorithm

Automation

Much of the time investment necessary to generate a CFD solution comes in the form of human intervention. Converting a CAD model into a form usable for CFD requires a good deal of manual modification. Generating a mesh from the modified CAD model is a labor-intensive process. Often, manual intervention is required in the middle of a CFD run if it appears that the mesh needs modification to accommodate changing flow characteristics. Once the CFD computation is complete, post-processing and extraction of relevant information from the solution require human guidance. The manual input required at each of these stages both slows the process down immensely and prevents its implementation as an internal routine in an optimization process. Because of the high overhead cost associated with generating a scale model for use in wind tunnel testing, CFD is cost-effective compared with physical testing for less than a few hundred test runs. Automation of the grid-generation process would make CFD cost and time effective up to a few thousand test runs, an order of magnitude improvement.

Automated grid generation generally makes use of unstructured grids. Higher order computational methods, well developed for structured grids, are still somewhat immature for unstructured grids. Another complexity involved in the use of unstructured grids is error estimation. While structured grid solvers can be formulated in such a way that estimates of the computational error are calculable, unstructured grids present a more challenging target for quantification of uncertainty because of their irregularity. The problem becomes even more complex for dynamically adaptive grids.

Dynamic grid adaptation would allow CFD solvers to refine the computational mesh only where necessary and as necessary, speeding up simulations by cutting down on unnecessary resolution and enabling solutions where current methods break down in response to changing flow conditions or geometries.

It bears particular note that advances in process automation, especially grid generation and dynamic grid adaptation, yield substantial benefits independent of other advances and apply equally to current and future CFD algorithms. Automatic grid generation is a necessary step in the incorporation of CFD into optimization routines.

Outline

- Study Overview
- Executive Summary and Review of Overall Findings
- Impact and History of CFD
- Metrics for Evaluating CFD Development
- Conclusions

Historic Impact of CFD

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CFD has:

- Decreased number of prototype variations required
- Allowed increasing complexity with limited growth in wind tunnel testing requirements
  - Increasingly sensitive/complex designs require more testing/analysis for success …
  - But, for fixed-wing aircraft, the number of wind tunnel tests has leveled at ~ 20,000 hours per system
  - CFD has allowed utilization of test budget for optimization and fine tuning
    - RAND study reported 50% reduction in prototype testing during early design phases
- Reduced number and magnitude of post-flight changes

CFD is widely used in aircraft design and has influenced the design process as shown in the slide. In fact, "CFD has proven an excellent tool for preliminary design configuration screening (simulation of conventional aircraft at cruise condition has allowed up to 50 percent reductions in physical testing at the screening stage…" (*Wind Tunnel and Propulsion Test Facilities,* RAND Technical Report TR-134-NASA/OSD). A footnote to the quoted sentence elaborates on screening:

Screening-stage reductions were cited by multiple industry design experts in response to our survey questions. See also Beach and Bolino (1994), Crook (2002), and Smith (2004) for additional discussions on the effects of CFD testing on WT/PT facility testing hours. However, the benefits of using CFD for initial screening and to improve testing efficiency do not necessarily indicate a reduction in overall WT/PT facility testing hours. Rather, a complementary CFD program presents an opportunity to shift more testing resources from preliminary explorations to final optimization. Respondents made it very clear that decisions on quantity of testing are primarily budget driven and that they will test as much as they can afford to address the range of technical concerns and reduce important risks when possible.

Use of CFD in Aircraft Design

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CFD Is Optimal For:	**CFD Is Not Yet Optimal For:**

CFD Is Optimal For:

- Rapid narrowing of design space
- On-design optimization
  - Incremental design comparisons
- Increments in lift and drag at cruise conditions
- Correlation of wind tunnel/flight-test data
  - Reynolds number effect

CFD Is Not Yet Optimal For:

- Performance optimization where areas of separated flow occur
- Dynamic and maneuvering flight regimes
- Fluid-structure interactions
- Aircraft design database generation
- Final design optimization and validation
- Final flight optimization and qualification

CFD has a number of specific applications, but more widespread use is limited due to the assumptions inherent in current (RANS) methods and the time it takes to generate a CFD solution.

Approaches to CFD

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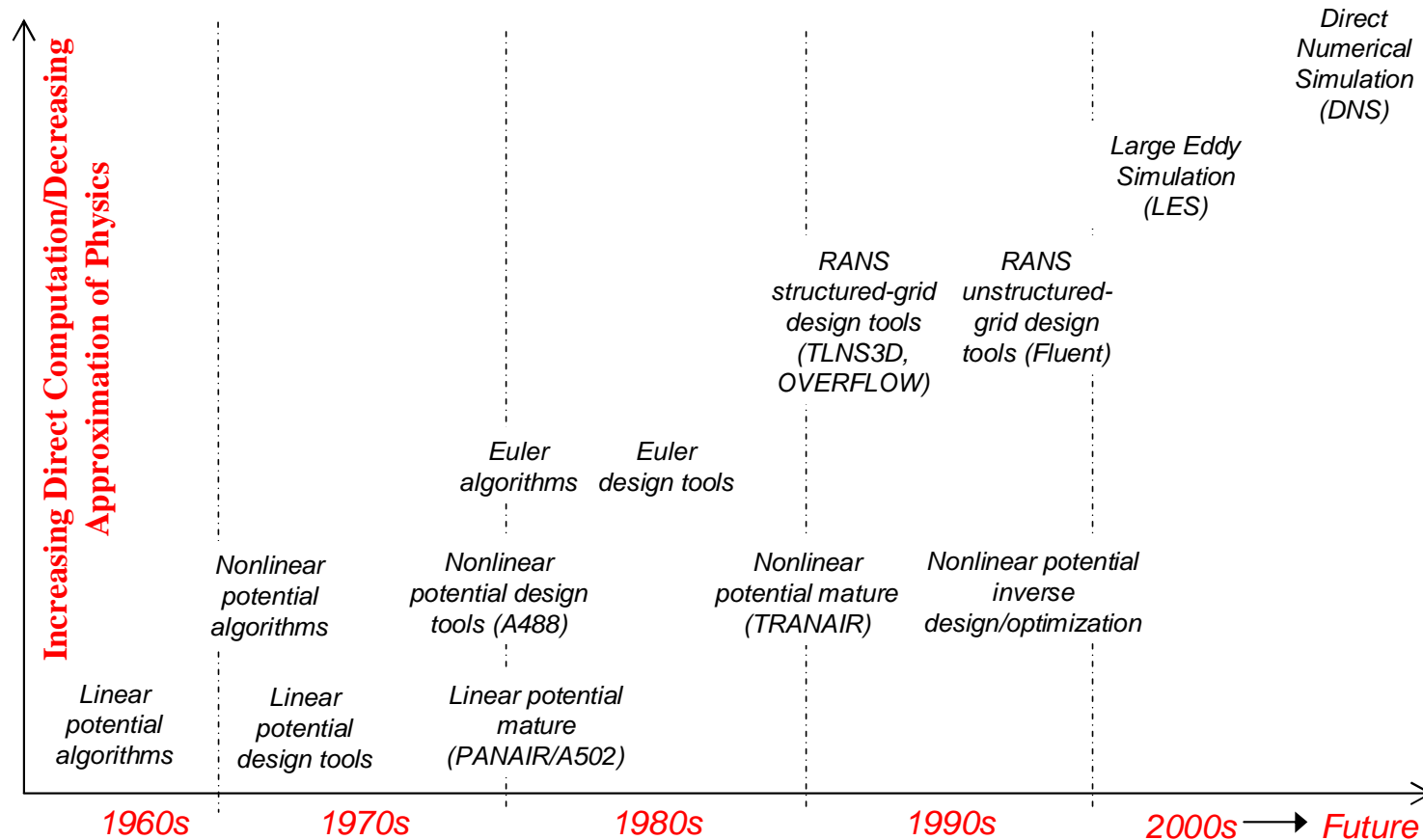In increasing complexity and fidelity:

- Potential methods
  - Assume irrotational, inviscid flow (no friction/dissipation, no vorticity)

- Euler
  - Assumes inviscid flow (no friction or dissipation)

- RANS
  - Assumes that turbulence can be represented by a mean state

- LES
  - Ignores small-scale vortex effects

- DNS
  - Full-up solution to the Navier-Stokes equations

A number of approaches to CFD have been used or considered over the past several decades. The primary approaches are listed in the slide. The current/near-term state of the art includes the following:

- *RANS*—Use of the RANS equations implies that the turbulent flow can be represented by a mean state. For stationary turbulence (a turbulent flow that does not vary in time on average), this is generally considered to be a good approximation. However, for unsteady flows (a flow that does vary in time), the use of the RANS equations is more questionable. RANS analysis is the current state of the art, and it is regularly applied, where appropriate.

- *LES*—In LES, the large-scale structure of turbulent flow is computed directly, and the smallest and nearly isotropic eddies are modeled and can be termed as subgrid scale eddies. This can be achieved by filtering the Navier-Stokes equations to obtain a set of equations that govern the resolved flow. Filtering is a type of space averaging of the flow variables over regions approximately the size of the computational control volume. Computational requirements for LES are approximately 10^3 times that of RANS but 10^{-5} that of DNS.

- *LES–RANS*—RANS utilizes a model to determine the effects of turbulence. LES directly calculates the larger turbulent eddies and utilizes a model for the smaller, uncalculated scales. Whereas larger scale vortices depend heavily on the geometry of the flow, contributing to the need for RANS recalibration for each geometry, turbulent eddies below the LES scale are comparatively consistent, depending principally upon the structure of the larger eddies, giving LES potential predictive capability on previously untested geometries.

Even when LES becomes a standard tool in predicting flow fields and calculating aircraft loads, especially in separated flow configurations, it seems likely that RANS and other lower fidelity models will persist in their usefulness in optimization tools and the like where many quick-turnaround computations are necessary. In these situations, LES could serve as a source of the data required to calibrate the RANS turbulence models.

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Time Line of CFD Development

Increasing Direct Computation/Decreasing Approximation of Physics

Direct Numerical Simulation (DNS)

Large Eddy Simulation (LES)

RANS structured-grid design tools (TLNS3D, OVERFLOW)

RANS unstructured-grid design tools (Fluent)

Euler algorithms

Euler design tools

Nonlinear potential algorithms

Nonlinear potential design tools (A488)

Nonlinear potential mature (TRANAIR)

Nonlinear potential inverse design/optimization

Linear potential algorithms

Linear potential design tools

Linear potential mature (PANAIR/A502)

1960s   1970s   1980s   1990s   2000s → Future

Linear potential codes (vortex-lattice, doublet-lattice, and panel methods) were first developed as a concept in the early 1960s. By 1973, panel-method codes were being used to support aircraft design. Linear potential codes are limited to inviscid, irrotational, and linear approximations of subsonic, attached flows. A NASA-funded project in the mid-1970s brought panel-method codes into maturity. A mature code, in this sense, is a code that is accepted in industry without additional wind tunnel validation; its shortcomings and assumptions are fully understood. Boeing's A502 software that emerged from that project is still used today in preliminary design studies and is accepted by the FAA for the certification of incremental changes to existing aircraft.

Nonlinear potential codes (transonic, small perturbation and full potential equations coupled with boundary-layer methods) were introduced in the early 1970s. Nonlinear potential codes had similar limitations to linear potential codes but could model transonic and mildly separated flows. By the early 1980s, full-potential, coupled boundary-layer methods were available for specific configurations or components but required expert users and very lengthy setup and run times. Proper grid generation and user intervention mid-run were particular problems. A NASA funded project in the mid-1980s led to the creation of the TRANAIR code at Boeing; it is one of the few nonlinear potential codes still in use today. TRANAIR is a hybrid panel method/full-potential equation code with solution-adaptive grid refinement and some aeroelastic modeling capabilities. It is still used extensively for performance modeling and design optimization of standard configurations.

Euler codes were rapidly developed in the 1980s to cover off-design conditions where significant shocks or rotational flows existed. Since they exclude viscous effects, however, Euler codes cannot inherently model transonic flows better than nonlinear potential codes and cannot estimate total drag or model separation. Due to the close relationship between Euler and Navier-Stokes equations (elimination of the diffusion terms converts Navier-Stokes equations to Euler equations), the same piece of software is often used for both methods.

Navier-Stokes methods are the only methods that can be used to simulate the entire flight regime. DNSs of the Navier-Stokes equations are currently too computationally intensive, however, so RANS methods coupled with turbulence models were developed in the late 1980s. By the early 1990s, RANS solvers on structured grids were available for industry use and could obtain a solution overnight. However, the RANS assumptions limit its usefulness as a predictive tool for the accurate simulation of flows where there is significant time dependency, as in high-lift and separated flows. LES algorithms, currently in development, would address some of the limitations of RANS with regard to separated and unsteady flows. However, LES algorithms still utilize simplifications to the full

Navier-Stokes equations. Practical LES implementations for problems as large as aircraft design are still years away and require improvements in computational speed, grid generation, and adaptive gridding to realize.

Sources

Johnson, Tinoco, and Yu. "Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes, Seattle." AIAA-2003-3439. 16th AIAA CFD Conference, 23–26 June 2003, Orlando, Fla.

Raj, Pradeep. "CFD at a Crossroads: An Industry Perspective." *Frontiers of Computational Fluid Dynamics—1998*. Ch 23. Ed. Caughey, David A. and Mohamed M. Hafez, World Scientific Publishing Co. Pte. Ltd. 1998.

LES Is the Next Major Step in CFD

- RANS is relatively mature. Thus, return on investment from further R&D in RANS-specific issues is likely to be low:
    - RANS-specific turbulence models show little promise of improving
    - Separated flows are not adequately captured
- LES is the next major step in CFD and is likely to become operationally relevant in 10–15 years:
    - LES solutions are expected to be readily available for aircraft design activities over the next 5–10 years.
    - LES is expected to achieve run times comparable to current RANS solutions in 10–15 years.
- Going forward, R&D investments in LES are likely to have higher payoff than in RANS:
    - LES captures separated flows
    - LES directly simulates large-scale turbulence (removing a significant contributor to RANS error)
- Several areas of investigation remain applicable regardless of simulation approach:
    - Understanding laminar to turbulent transition
    - Grid generation
    - Dynamic grid adaptation

Based on the team's interviews and analysis of CFD capabilities, the team concluded that LES is likely to become the dominant computational approach for leading-edge CFD applications over the next 20 years. But while LES itself requires further development, ancillary research and development will also be required to fully develop CFD capabilities.

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# *Possible Metrics for Measuring Influence of CFD*

- Number of prototype variations required
- Wind tunnel time
- Computational requirements and capabilities
- TRLs
- Cost and time per data point
  - CFD
  - Physical test

The team assembled a number of different approaches to measuring the development of CFD—both historically as well as for projections into the future. The metrics on this slide are further discussed on the following charts.

Number of Wing Variations Decreased

The Impact of CFD on Configuration Lines Development Wind Tunnel Testing
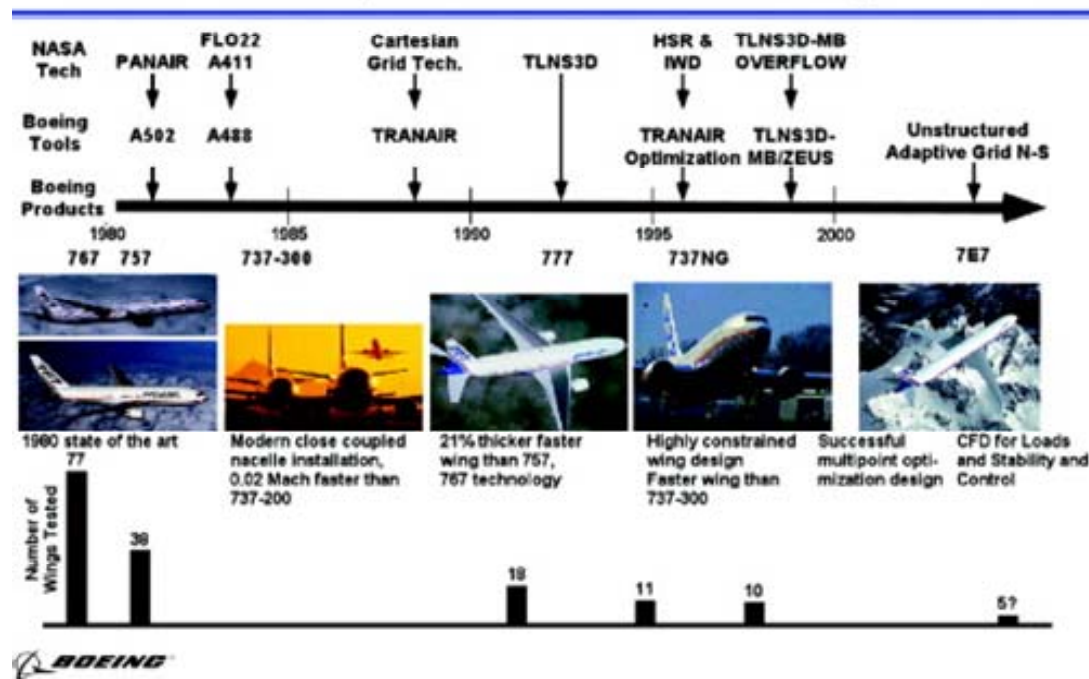
Source: *Aviation Week and Space Technology,* 8 December 2003; online, available: http://www.nitrd.gov/subcommittee/hec/hecrtf-outreach/sc03/sc03_hecrtf_dball.pdf

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This chart is from an *Aviation Week and Space Technology* article (8 December 2003) on CFD and aircraft design. The figure shows the reduction in the number of wing designs that were tested for various Boeing aircraft over the last 25 years. The number has decreased from 77 for the 767 aircraft to fewer than 5 for the new 787.

The figure also shows the computational codes that enabled this reduction in different wings that had to be tested. The codes used in 1980 (left side of the figure) were potential codes that did not capture the viscous effects (i.e., drag). The codes progress to the current state of the art and beyond (unstructured, adaptive-grid Navier-Stokes codes).

Wind Tunnel Time
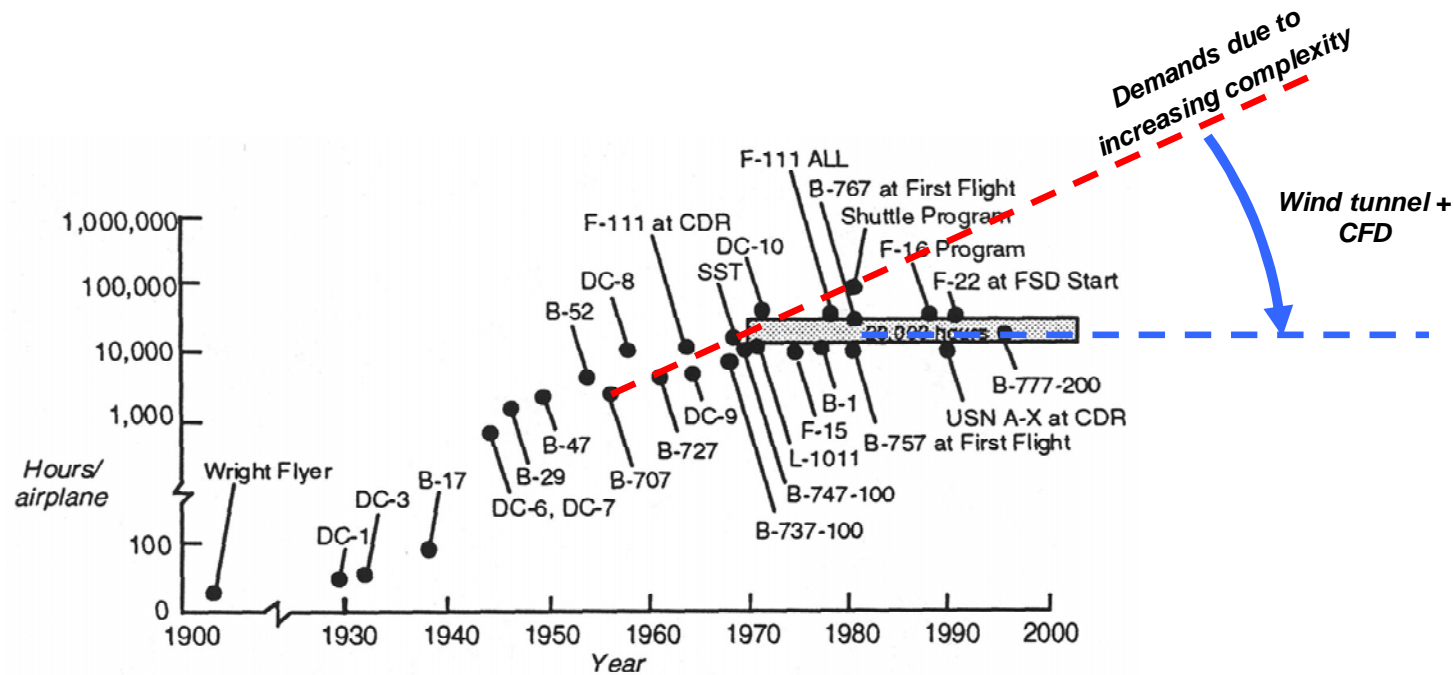
Source: Figure 9. *DOD Aeronautical Test Facilities Assessment,* March 1997

This graph shows the wind tunnel hours used in the design and development of the aircraft listed. While the expected trend of increasing complexity and reduced design margins would lead to more wind tunnel testing, CFD has been used to maintain an essentially constant number of wind tunnel test hours for the last 30 years. Also, while the number of different wing designs that need to be tested has been reduced significantly (see previous slide), the wind tunnel usage has not reflected a reduction in required testing. The graph shows that the wind tunnel test hours have leveled off between 10,000 and 40,000 hours for the typical aircraft design.

There are a number of reasons that wind tunnel testing has continued to dominate aircraft development despite significant improvements in the analytical/computational design tools. First, the time and cost required to generate all the data needed for a complete design using CFD are still much too great for current methods. Second, CFD cannot accurately predict all the data required in the aircraft design process, so wind tunnel testing is still required to complete the data matrix. Since the model needs to be built anyway—and that initial cost is the driving factor in the cost of wind tunnel testing—it makes schedule and cost sense to use wind tunnel testing to generate the required data. Third, because of increased design complexity and reduced design margins for the current designs, more testing is required to validate CFD results and to gather data at the edges of the predicted flight envelopes. However, CFD has contributed significantly to effective selection and optimization of preliminary designs and thereby helped control the number of wind tunnel test hours despite increasing design complexity and more stressing flight characteristics.

By improving CFD timeliness and expanding the areas where it can provide engineering data it is hoped that, in the future, test hours can be reduced.

CFD and Flow Physics

Flow Physics Situation	Vehicle Characteristic Affected
Attached Turbulent Boundary Layer – Re Number Effects – Skin Friction	Skin friction drag
Shockwave Characteristics – Pressure rise and turbulence – Shock position / movement	Sonic boom for supersonic vehicles Aero meeting Flow control concepts for reducing shock drag
Vortex Phenomena – Vortex / viscous interactions – Wake vortex characteristics – Interaction with downstream components	**Key Rotorcraft Area** Airframe noise levels Undesirable unsteady flows Aircraft spacing at takeoff and landing
Flow Merging and Mixing – Multielement high-lift systems – Propulsive jet interactions	Maximum lift capability Interference drag Stability and control characteristics
Viscous flow separation onset and progression – Leading- and trailing-edge separation – Juncture flow separation	Buffet onset and progression characteristics; drag; nonlinear stability and control characteristics; flutter
Fully Separated Flows – Base flows – Wakes behind bluff bodies	Noise sources Drag Post-buffet onset / progression
Boundary Layer Transition – Transition fixing (viscous simulation) – Laminar vs. Turbulent separation – Wind tunnel and noise effect	Drag Maximum lift Stability and control characteristics
Ice Accretion Effects – Ice accretion typically irregular and computed shapes do not match measured	Maximum lift / stall margin Drag Flight safety

Flow Physics Handled Well by CFD

Flow Physics Not Handled Well by CFD

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The table contains data from the Rand report, "Wind Tunnel and Propulsion Test Facilities," by Philip Anton (MG-178). The table summarizes areas where computational analysis still needs development. In the two areas where CFD solutions have proven accurate and reliable, they have made an impact on the aircraft design process. These areas are attached flows and supersonic shock characteristics.

The first four items on the bottom half of the table—vortex phenomena, flow merging and mixing, viscous separation, and fully separated flows—are time-dependent phenomena and, as such, are not handled well by RANS analysis. Based on our interviews and research, we conclude that RANS does not appear to be able to provide an adequate solution for these problem areas. LES algorithms are predicted to improve the analysis of separated flows, but are much more computationally intensive. Specifically, LES algorithms are predicted to require a three-orders-of-magnitude increase in computation time over RANS.

The last two areas—boundary layer transition and ice accretion—are issues which moving to different CFD algorithms—such as LES—will not solve and that need to be addressed separately. Ice accretion is especially difficult because of the wide range of atmospheric conditions that have to be incorporated into the analytical model to accurately predict the ice buildup.

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CFD Capabilities Projection

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Projected Times to Complete Single CFD Calculation
>75,000 Runs Required to Complete Aircraft Design Database
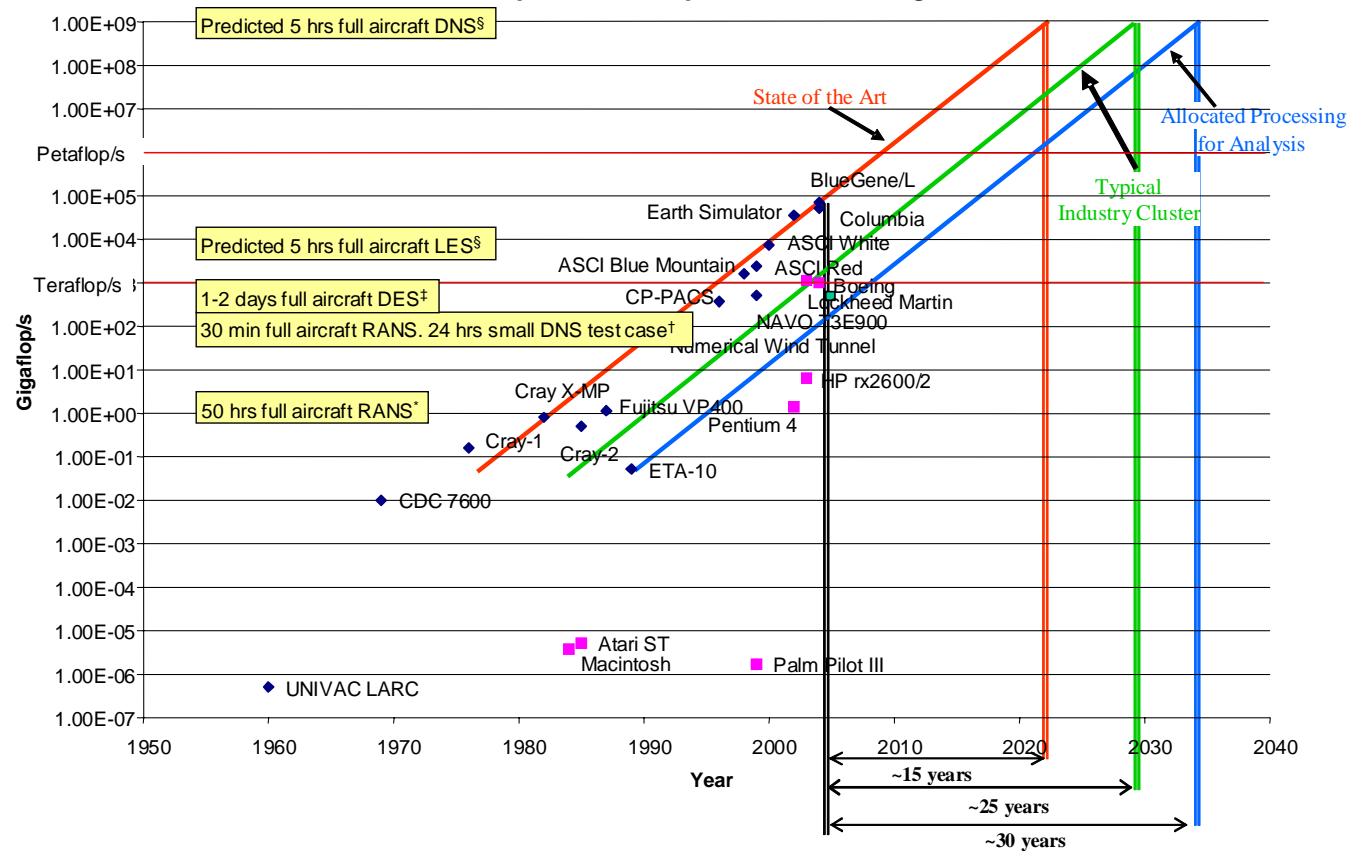
Computer speed is measured in billion floating point operations per second (Gflop/s) obtained using a Linpack benchmark. Scores are taken from top500.org and Linpack's database performance.netlib.org. In-house computing clusters used in industry (see pink Lockheed and Boeing squares) are two orders of magnitude slower than the state-of-the-art supercomputers. The team estimates that 1/10th of the total cluster resources are available to any given problem (blue line). If computing speed continues to increase exponentially, it will be 15 years before LES is standard practice (one solution obtained in 30 minutes using resources allocated for analysis) and 15 years before a DNS solution can be obtained in 5 hours on the fastest supercomputers.

Yellow boxes designate the time to run *one* full-aircraft CFD simulation at *y* Gflop/s. Hundreds to thousands of CFD simulations are currently run when designing an aircraft (although not all on a full-aircraft grid); fully testing a design without a wind tunnel would require over 75,000 simulations.

While a LES on a full aircraft grid is theoretically possible today using the full resources of the fastest supercomputers, LES and DNS algorithms for full aircraft simulations have not yet been developed. The computational resource predictions for LES and DNS are based on Reynolds-number scaling on flat-plate models and are not necessarily extendable to more complicated geometries. It is possible that the resources needed for complex LES and DNS simulations will increase as the software is developed and additional hurdles are discovered.

CFD run times are taken from the following sources:

[§]DoD Aeronautical Test Facilities Assessment, March 1997

[‡]512 processors on the NAVO T3E900; see Squires, K.D., et al,. "Analysis of Full Aircraft with Massive Separation Using Detached-Eddy Simulation," 2002.

[†]Numerical Wind Tunnel; see Miyoshi, H., et al., "Development and Achievement of NAL Numerical Wind Tunnel (NWT) for CFD Computations," *IEEE,* 1994.

[*]Fujitsu VP400; see Miyoshi, H., et al. "Development and Achievement of NAL Numerical Wind Tunnel (NWT) for CFD Computations," *IEEE,* 1994.

LES and DNS resource predictions are based on the grid scale required to resolve the smallest eddy of interest in flow around a flat plate. For DNS the number of nodes scales with $Re^{9/4}$. For LES the number of nodes scales with $Re^{0.4}$ in the outer layer, where viscous effects are not important, and with $Re^{1.8}$ in the inner layer, where viscous effects dominate. The computational cost for a particular algorithm depends on the number of operations per node and the time scale. The number of operations scales like the number of grid points, and the time scale is inversely proportional to the smallest eddy length scale. This results in a computational cost that scales like (grid size)$^{4/3}$. For DNS, the total computational cost scales with Re^3, and for LES, the outer layer cost scales with $Re^{0.5}$, and the inner layer scales with $Re^{2.4}$. (Ugo Piomelli and Elias Balaras, "Wall-Layer Models for Large-Eddy Simulations," *Annu. Rev. Fluid Mech.* 2002, 34:349–74)

TRL Descriptions for CFD

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	TRL	Analysis/Simulation
Implementation	9	Actual system "proven" through successful analysis operations
Validation / Verification	8	Actual system completed and "qualified" through test and demonstration analyses
	7	System prototype demonstration in a design environment
System Demonstration	6	System/subsystem model or prototype demonstration in a relevant design environment
	5	Component validation in relevant environment
System Development	4	Component validation in "laboratory" environment
Research to Prove Feasibility	3	Analytical and experimental critical function and/or characteristic proof-of-concept
Basic Technology Research	2	Technology concept and/or application formulated
	1	Basic principles observed and reported

Adapted from DoDI 5000.2-R

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Technology Readiness Level Assessment was originally development by NASA as a means to assesses the state of a product's development. A modified TRL process has been incorporated into the DoD Technology Readiness Assessment (TRA) process. (For reference, Budget Activities (BA) 1, 2, and 3 are concerned with products and systems that have TRLs 1 through 6. In the current DoD acquisition model, TRL 6 for all technologies is desired by Milestone B.)

The TRL scale runs from TRL 1 (basic principle observed) to TRL 9 (actual proven system), with steps in between that describe various levels of development. For the current task, a TRL scale was modified to capture some of the specific qualities of algorithm development. This scale was sent to CFD experts, and their assessment of CFD was requested. As with any assessment tool that requires qualitative assessment, ours will have a spread of responses.

Data Categories

Flight Configurations/Analyses	General Data Needs
• Aero cruise design • Landing / takeoff • Maneuver performance • Stores release • Environmental control system • Icing	• Loads • Stability and control • Propulsion integration • Flutter • Noise • Aerothermal analysis

CFD experts were asked to evaluate the TRL of CFD with respect to these data categories.

Flight Configurations/Analyses

- *Aero Cruise Design*—Steady level flight has a minimum of separated flow and no time dependence, and drag estimates in this phase of flight dominate the estimated fuel cost of operating the aircraft.

- *Landing/Takeoff*—These high-lift configurations often have large regions of massively separated flow and elements of time-dependence, making computation more difficult.

- *Maneuver Performance*—Inherently time-dependent flow and often massively separated flow make computation difficult. This area is particularly crucial to military aircraft where maneuver is a central element of the aircraft's capability requirements. Maneuvering is important for commercial aircraft, but is not a primary design segment. Much of the maneuver testing gets done when the landing and takeoff testing is done since this is when the aircraft does most of its maneuvers.

- *Stores Release*—Safe release of external or internal weapons, fuel tanks, or cargo requires modeling of the inherently time-dependent flow as the item separates from the aircraft. Vibration or acoustic modeling of open cavities during internal stores release can also be important.

- *Environmental Control System (ECS)*—ECSs deal with how temperatures are controlled inside an aircraft. There are two aspects to the ECS: (1) how excess heat is removed from the aircraft and (2) how heated air is moved around inside. This system can be critical and has caused problems on numerous aircraft (either things get too hot or not hot enough). Wind tunnel testing is necessary because the heat transfer and flow into cooling ducts are very dependant on the type of flow (laminar or turbulent boundary conditions) and the flow field. There are other tests that these are sometimes coupled with for signature investigations.

- *Icing*—Icing deals with the formation and removal of ice along the surface of the aircraft and the resulting changes in aircraft performance. Icing is important to commercial aircraft, but less so to fighter aircraft. Typically, fighters are much smaller (and therefore easier to deice), do not have to wait for extended amounts of time between being deiced and takeoff, and generally fly much faster through the atmospheric conditions that cause icing than commercial aircraft (the landing pattern is much more compact).

General Data Needs

Loads refers to the lift, drag, and pitching moment on the aircraft at various angles of attack and flight conditions.

Stability and control refer to the stability of each flight configuration and the reaction of the aircraft to movement of the control surfaces. This is necessary for development of control schemes, especially for inherently unstable, computer-stabilized aircraft (fly-by-wire).

Propulsion integration requires understanding of engine inlet and outlet flows.

"Flutter" refers to undesirable oscillatory movement of flexible parts of the aircraft under flight conditions. Fluid-structure interaction and time-dependent behavior are two of the essential components of flutter calculation.

Noise calculations can be important both for comfort and safety of passengers and people on the ground as well as understanding of acoustic signatures for detection avoidance.

Aerothermal analysis calculates flow-induced heating and cooling of various portions of the airframe and affects material selection, environmental control systems, engine performance, engine cooling requirements, and shock behavior.

CFD TRL Analysis

Data Category	CFD used to provide design-process-quality results?	TRL of CFD	Limiting factors for expanded CFD usage
• Aero cruise design	• Yes	• High	• Turbulence models • Still requires flight validation
• Landing / takeoff	• Partial	• Medium/ high	• Turbulence models • Fundamental understanding of separation onset and evolution

• Maneuver performance	• No	• Low	• Turbulence models
			• Time dependent flow and aircraft motion
			   – Aeroelastic / Flexible Structures Coupling w/CFD Tool
			   – Adaptive gridding and computation in unstructured grids

• Stores release	• Partial	• Medium	• Lack of experimental data • Fundamental understanding of separation onset and evolution • Acoustic modeling of cavities
• Environmental Control System	• Yes	• Medium/ high	• Complex interactions between different systems—often easier just to build and test a physical model • Improved boundary-layer transition prediction/model
• Icing	• Partial	• Medium	• Ice buildup processes • Turbulence models • Fundamental understanding of separation onset and evolution

This table and the table on the next page represent the feedback received from CFD experts regarding the TRL for different types of CFD computations. Based on the feedback received, the team characterized TRL values as follows:

7 to 9 = High

4 to 6 = Medium

1 to 3 = Low

In general, the feedback was quite consistent across respondents, giving the team a reasonable level of confidence in the usefulness of the TRL methodology overall as well as in the specific results.

Note that the TRL ranges given represent rough aggregations of feedback that applied to primarily to commercial and military transonic aircraft, although the team did receive a limited amount of feedback regarding hypersonic aircraft. In general, the TRL ranges are lower (much lower, in some cases) when CFD is applied to hypersonic aircraft than when applied to transonic military and commercial aircraft.

Also note that a "high" TRL range does not indicate that CFD can function in the absence of wind tunnels. Instead, these scores indicate that the current generation of CFD codes (which are primarily RANS codes) are relatively mature, the results can be readily interpreted without further wind tunnel validation, and the limitations are well understood. As a result, these analyses are readily used in the aircraft design process.

As pointed out elsewhere, however, there remain practical limitations (e.g., accuracy, time, and cost) to exclusive reliance on the CFD tools.

CFD TRL Analysis

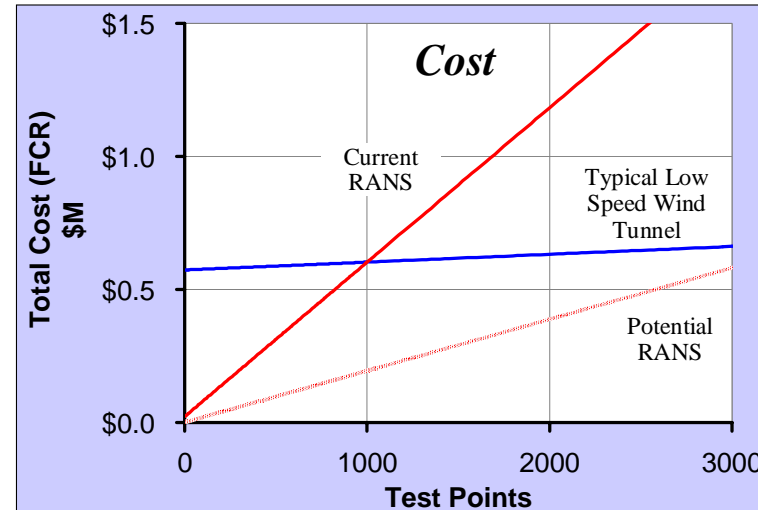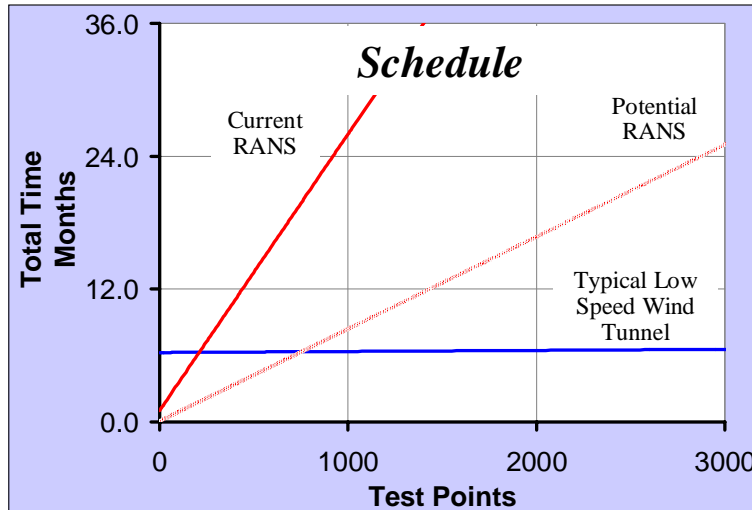| Data Category	CFD used to provide design-process-quality results?	TRL of CFD	Limiting factors for expanded CFD usage
• Loads	• Yes	• Medium/ High	• Computational power (integrating individual data into overall assessment) • Aeroelastic deformations
• Stability and control	• Partial	• Medium	• Integration of CFD and structural analysis models • Fundamental understanding of separation onset and evolution • Adaptive gridding and computation in unstructured grids • Time dependent flow and aircraft motion
• Propulsion integration	• Partial	• Medium/ high	• Boundary layer transition model • Flow-control device modeling
• Flutter	• Partial	• Low/ medium	• Time dependent flow and aircraft motion • Fluid/structure interactions (potentially nonlinear) • Adaptive gridding and computation in unstructured grids
• Noise	• Partial	• Low	• Higher order methods/LES development • Adaptive gridding and computation in unstructured grids • Vortex interactions
• Aerothermal analysis	• No	• Medium/ low	• Poor understanding of chemistry in extreme environments (hypersonics) • Boundary-layer transition

Low-to-medium TRL values correspond to flight regimes dominated by turbulent flow, transient conditions, multi-physics problems, or uncertainties due to lack of experimental data.

Limiting factors are driven by several major challenges:

- Overwhelming computational resources required to mitigate the effect of turbulence models.
    - Significantly increased grid resolution may mitigate inadequacies in current turbulence models.
    - LES eliminates large-scale turbulence model problems.

- Tremendous computational resources demanded by fully transient solutions:
    - Rotorcraft dynamics.
    - Maneuvering aircraft.
    - Direct modeling of turbulence.

- Extensive computational resources demanded by the introduction of additional physics:
    - Flutter/aero-elasticity (fluid-structure interaction).
    - Icing.
    - Reacting flow (hypersonics).
    - Heat transfer (hypersonics).
    - Far-field noise prediction (especially challenging for rotorcraft).

- Inadequate understanding of transition from laminar to turbulent flow—current methods use separate physics model to predict transition location.

- Uncertainties due to lack of relevant experimental data for simulation validation (challenge primarily to hypersonics):
    - Dearth of ground testing facilities.
    - Expense of flight testing.
    - Inability to gather extensive data from flight testing.

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- Inability to automatically generate and adapt quality grids to capture transient fluid motions and boundaries. This is compounded by the need to estimate convergence errors, which is more difficult for unstructured grids.

CFD/Wind Tunnel Cost/Schedule Comparison

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Schedule

Total Time Months — 36.0, 24.0, 12.0, 0.0

Test Points — 0, 1000, 2000, 3000

Current RANS, Potential RANS, Typical Low Speed Wind Tunnel

Cost

Total Cost (FCR) $M — $1.5, $1.0, $0.5, $0.0

Test Points — 0, 1000, 2000, 3000

Current RANS, Typical Low Speed Wind Tunnel, Potential RANS

- Fixed initial cost and time investment of fabricating a wind tunnel model exceeds corresponding initial cost and schedule for CFD modeling
- Once model exists, wind tunnel testing generates data far more rapidly and has a lower marginal cost per data point than CFD.
- CFD is extremely useful (because it's less expensive and faster) for small studies with 200–400 data points and where the data requirement is within the reach of current CFD capabilities.
- LES
  - Expands reach of simulations
  - Does *not* reduce cost or time for CFD
- Faster computing
  - Increases data set size for wind tunnel/CFD crossover
  - Full aircraft data set construction is well beyond near-term projections of wind tunnel/CFD crossover

	CFD	Wind tunnel
Start-up time	Low	High
Start-up cost	Low	High
Marginal time	High	Very low
Marginal cost	High	Low
Forte	Small data sets	Large data sets

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The team modeled the cost and time to obtain CFD data points vs. the cost and time to gather those points by wind tunnel testing. As the graphs indicate, CFD is only competitive with wind tunnels on a cost and schedule basis when a few data points are needed. The largest cost driver for wind tunnels is the model fabrication cost, while the dominant cost driver for CFD is the length of time to generate one data point (CPU time plus time moving files, setting initial conditions, changing grid, etc.). With an entire aircraft development cycle requiring hundreds of thousands of test points, current CFD methods will not come close to being cost competitive with wind tunnels even with dramatic increases in computer speeds. This includes optimization studies that overall may have more data points than the wind tunnel/CFD crossover, but change the geometry over the course of the optimization and therefore cannot take advantage of the economy of scale of a wind tunnel once the model is built. In addition, RANS models are not capable of modeling the entire flight regime and therefore physically cannot replace some categories of wind tunnel tests, regardless of cost or schedule.

The state-of-the-art RANS cost was calculated by taking the time it takes to generate the initial grid, plus a run time of 5.5 hours, plus 1.0 hours of human intervention per run, all multiplied by the cost of one engineer at $145 per hour (fully burdened hourly rate for a senior analyst). The setup time was estimated to be 4 weeks, but the total CFD cost is highly insensitive to these initial costs. The potential future RANS cost was found by using a setup time of 8 hours, a 1 hour run time, and 0.5 hours of hands-on time per run instead.

Wind tunnel cost curves are based on advertised charges per polar for typical wind tunnels listed in AIAA-94-2474, "National Planning for Aeronautical Test Facilities," and updated for inflation. Full cost recovery curves were obtained by adding an estimated yearly maintenance charge amortized per data point. The wind tunnel was estimated to cost $1M per year to maintain and to have a typical occupancy of 3,000 hours per year. The wind tunnel was assumed to allow 2.5 polars per hour. The personnel costs were estimated to be $145 per person per hour and assumed a test crew of 6 persons. Wind tunnel costs are dominated by the initial model fabrication costs, as demonstrated by the flat slope and the small change when full cost recovery is included.

Variations of input parameters for CFD and wind tunnel testing, including the engineer's hourly rate, yearly wind tunnel support costs, and time to fabricate wind tunnel model, were run and resulted in relatively minor changes in the crossover point for either current RANS or future RANS cases. Irrespective of the cost or schedule crossover points, because RANS CFD is not capable

of simulating all of the data points necessary in a full aircraft design, to gather these data now and in the future (i.e., the next 25 years), wind tunnel testing will still be required to put together a complete aircraft design database

Outline

- Study Overview
- Executive Summary and Review of Overall Findings
- Impact and History of CFD
- Metrics for Evaluating CFD Development
- Conclusions

Conclusions

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- CFD has had a major effect on aircraft design process
  - Reduced wind tunnel hours in preliminary design
  - Optimized designs arrived at more quickly and at reduced costs

- CFD is not likely to be able to replace ground testing in the near future
  - Currently, CFD cannot simulate all data necessary for aircraft design
  - When CFD can provide design-quality data, the time required to generate the required data by CFD is prohibitively long compared with wind tunnel testing

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Conclusions

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- RANS algorithms are mature
  - RANS use has become standard in aircraft design processes
  - Limitations due to physics assumptions in RANS algorithms limits its ability to capture other areas of need
    - Separated flows, time-dependent flows

- LES algorithms have potential to allow effective simulation of areas not currently solvable by RANS and will become computationally relevant over the next 20 years

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14. ABSTRACT

The authors review the current status and projected future performance of computational fluid dynamics (CFD) as applied to aircraft design. Currently, CFD is effective at predicting aircraft performance at cruise conditions, narrowing the design space for preliminary airframe design, and validating incremental changes to existing designs. However, current methods cannot accurately simulate all flight conditions, nor can they provide the volume of data required for full aircraft design in a timely and cost-effective manner relative to wind tunnels. Furthermore, confidence in CFD simulations is unavoidably reliant on validation from physical test data. The authors identify potential directions for CFD development and project rough time scales for the development of capabilities based on trends in the development of computing power and computing algorithms.

15. SUBJECT TERMS

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